

A simplified view of blazars: the γ -ray case.

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ABSTRACT

We have recently proposed a new simplified scenario where blazars are classified as flat-spectrum radio quasars (FSRQs) or BL Lacs according to the prescriptions of unified schemes, and to a varying combination of Doppler boosted radiation from the jet, emission from the accretion disk, the broad line region, and light from the host galaxy. Here we extend our approach, previously applied to radio and X-ray surveys, to the γ -ray band and, through detailed Monte Carlo simulations, compare our predictions to *Fermi*-LAT survey data. Our simulations are in remarkable agreement with the overall observational results, including the percentages of BL Lacs and FSRQs, the fraction of redshift-less objects, and the redshift, synchrotron peak, and γ -ray spectral index distributions. The strength and large scatter of the oft-debated observed γ -ray – radio flux density correlation is also reproduced. In addition, we predict that almost 3/4 of *Fermi*-LAT BL Lacs, and basically all of those without redshift determination, are actually FSRQs with their emission lines swamped by the non-thermal continuum and as such should be considered. Finally, several of the currently unassociated high Galactic latitude *Fermi* sources are expected to be radio-faint blazars displaying a pure elliptical galaxy optical spectrum.

Key words: BL Lacertae objects: general — quasars: emission lines — radiation mechanisms: non-thermal — radio continuum: galaxies — gamma-rays: galaxies

1 INTRODUCTION

Blazars are a small subclass of Active Galactic Nuclei (AGN) characterized by distinctive and extreme observational properties, such as large amplitude and rapid variability, superluminal motion, and strong emission over the entire electromagnetic spectrum. These peculiar sources are known since the discovery of QSOs (Schmidt 1963), as 3C273, the first quasar to be discovered, is in fact a well known blazar. A major distinction between QSOs and blazars is that while the former type of AGN mostly emit radiation through accretion onto a supermassive black hole, blazars also host a jet that is oriented closely along the line of sight, within which relativistic particles radiate losing their energy in a magnetic field (Blandford & Rees 1978; Urry & Padovani 1995). This jet component is responsible for the non-thermal emission from radio to high-energy γ -rays and for the extreme properties listed above when the viewing angle is small. When this angle is larger than $15 - 20^\circ$ the relativistic

amplification and superluminal effects are much less important and jet emission across the electromagnetic spectrum, although still present, may not be dominating the flux at IR, optical and X-ray frequencies where other nuclear and non-nuclear components emerge. Under these conditions the source is usually called a radio galaxy.

Although blazars represent a small minority of AGN, the interest in these sources is growing as they are being found in increasingly large numbers in high Galactic latitude surveys performed at microwave and γ -ray energies (Giommi et al. 2009; Abdo et al. 2010a; Planck Collaboration et al. 2011a). Blazars represent also the most abundant population of extragalactic sources at TeV energies¹.

Due to the blend of accretion disk, jet and host galaxy emission that is often present in their optical spectrum, the classification of blazars based on observational properties is a complex issue. This has resulted in some confusion in the literature.

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In a recent paper Giommi et al. (2012a, hereafter Paper I) examined the various argumentations and the experimental evidence behind the classification of blazars that have appeared in the literature, and proposed a new scenario, which is based on optical/UV light dilution, minimal assumptions on the physical properties of the non-thermal-jet emission, and unified schemes. These posit that BL Lacs and flat-spectrum radio quasars (FSRQs) are mostly low-excitation (LERGs)/Fanaroff-Riley (FR) I and high-excitation (HERGs)/FR II radio galaxies with their jets forming a small angle with respect to the line of sight (see Buttiglione et al. 2010, and references therein, for a discussion on LERGs and HERGs). We call this new approach the *simplified blazar view*. By means of detailed Monte Carlo simulations, Paper I showed that this scenario is consistent with the complex observational properties of blazars as we know them from all the surveys carried out so far in the radio and X-ray bands, solving at the same time a number of long-standing issues.

In this paper we extend the Monte Carlo simulations presented in Paper I to the GeV γ -ray band and compare our expectations with the AGN data in the *Fermi*-LAT 2-yr source catalogue (Nolan et al. 2012; Ackermann et al. 2011b; Shaw et al. 2013, hereafter 2LAC) and the *Fermi*-LAT data of a sample of radio selected blazars (Giommi et al. 2012b; Planck Collaboration 2011b). We note that simulations in the γ -ray band are more complex than those in the X-ray band since the γ -ray flux of blazars is not due to simple synchrotron or synchrotron-self-Compton emission, but is usually attributed to inverse Compton scattering of synchrotron and of external photons, or to the superposition of more than one component. Furthermore, the γ -ray flux is a much broader-band measurement and is subject to the highest source variability.

Table 1 summarizes the *simplified blazar view* proposed in Paper I. Sources with their jets forming small angles w.r.t. the line of sight ($\theta < \theta_{\text{blazar}} \sim 15 - 20^\circ$; Urry & Padovani 1995), and therefore dominated by non-thermal emission, are characterized by low values of the equivalent width (EW) and/or the so-called Ca H&K break, the latter being a stellar absorption feature found in the spectra of elliptical galaxies. However, only LERGs belonging to this class are real BL Lacs, that is have intrinsically weak emission lines. HERGs, which are supposed to have an accretion disk and therefore to display strong emission lines, *appear* to show weak lines only because these are swamped by non-thermal emission and are therefore “masquerading” BL Lacs (*italics* in the table) and are in fact misclassified FSRQs. Sources with somewhat weaker jet dilution still oriented at small angles show some optical features, like the emission lines typical of FSRQs. In this category we find also “masquerading” radio galaxies, that is sources, which are “bona fide” blazars but have their non-thermal emission in the optical/UV part of the spectrum swamped by the host galaxy. Finally, misdirected jets characterize the true radio galaxy population.

In short, starting from truly different objects like LERGs and HERGs, the combination of viewing angles and strong/weak optical/UV light dilution from the jet,

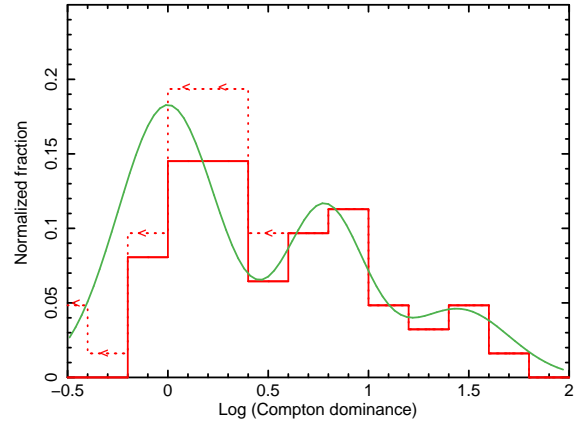


Figure 1. The distribution of the logarithm of Compton Dominance in the sample of radio selected blazars of Giommi et al. (2012b) with $\nu_{\text{peak}}^S < 10^{14}$ Hz. The red solid histogram shows the blazars detected by *Fermi*-LAT, while the dotted histogram represents upper limits for γ -ray undetected blazars. The green line is the function that represents the entire population of radio selected blazars used for our simulations.

determines the commonly adopted classification as FSRQs, BL Lacs, or radio galaxies. This purely observational approach in a number of cases assigns the same class to intrinsically different objects.

Throughout this paper we use a Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.27$ and $\Omega_\Lambda = 0.73$ (Komatsu et al. 2011).

2 SIMULATIONS

Our goal is to estimate the properties of a γ -ray flux-limited blazar sample, building upon the simulations presented in Paper I. We start by simulating blazars in the radio band applying the same ingredients used in Paper I and then estimate their γ -ray properties. To do so we must take into account a series of constraints that are directly determined from *Fermi*-LAT observations of well-defined radio selected samples of blazars. Namely:

- (i) the redshift distributions of radio selected and γ -ray selected blazars are very similar (see Fig. 13 of Ackermann et al. 2011b); moreover the redshift distributions of *Fermi*-detected and undetected radio selected blazars are also not significantly different (Lister et al. 2011);
- (ii) a significant fraction ($\sim 30 - 40\%$) of radio selected blazars (mostly FSRQs) are not detected even in the deepest *Fermi*-LAT observations (Lister et al. 2011; Giommi et al. 2012b);
- (iii) the ratio between inverse Compton and synchrotron peak luminosities, usually known as Compton Dominance (CD), is crucial to predict the γ -ray intensity of a blazar from its radio flux. Giommi et al. (2012b) showed that the CD distribution of radio selected blazars is very different below and above $\nu_{\text{peak}}^S = 10^{14}$ Hz, where ν_{peak}^S is the peak frequency of the synchrotron power. Fig. 1 (adapted from Fig. 22 of Giommi et al. (2012b)) shows this distribution for blazars with $\nu_{\text{peak}}^S < 10^{14}$ Hz. The red solid histogram refers to all radio selected blazars

Table 1. The *simplified blazar view* scenario. See text for details.

	LERG	HERG	viewing angle
strong jet dilution ($EW < 5 \text{ \AA}$; $Ca \text{ H\&K} < 0.4$)	BL Lac	<i>BL Lac</i> ⁽¹⁾	$\theta < \theta_{\text{blazar}}$
weak jet dilution	<i>radio galaxy</i> ⁽²⁾	FSRQ	$\theta < \theta_{\text{blazar}}$
misdirected jet	radio galaxy	radio galaxy	$\theta > \theta_{\text{blazar}}$

Italics denote “masquerading” sources (see text), ⁽¹⁾ misclassified FSRQ, ⁽²⁾ misclassified BL Lac

that were detected by *Fermi*-LAT. The dotted histogram refers instead to upper limits derived from the Spectral Energy Distribution (SED) of those blazars that were not detected even after 27 months of *Fermi*-LAT observations (see Giommi et al. 2012b, for details). These undetected γ -ray sources represent a significant fraction of the sample and certainly cannot be ignored. The green line is our educated guess of the underlying intrinsic distribution. The CDs of blazars with $\nu_{\text{peak}}^S > 10^{14}$ Hz (which are all detected in the γ -ray band) are instead clustered around ~ 1 (see Fig. 22 of Giommi et al. 2012b). We assume here that their distribution is represented by a gaussian with $\langle CD \rangle = 0.9$ and $\sigma = 0.4$.

(iv) the sensitivity of *Fermi*-LAT is a strong function of the γ -ray spectral index Γ (see, e.g., Fig. 14 of Ackermann et al. 2011b). We therefore need to estimate the latter parameter as well. Since we know that for blazars this correlates strongly with ν_{peak}^S (e.g., Fig. 29 of Abdo et al. (2010b) and Fig. 17 of Ackermann et al. (2011b)), we use that dependence for our purposes. By fitting the data of Fig. 17 of Ackermann et al. (2011b) we derive $\Gamma = -0.22 \times \log(\nu_{\text{peak}}^S) + 5.25$, with a dispersion $\sigma = 0.15$.

2.1 The dependence of γ -ray flux on radio flux density

The dependence of γ -ray flux on radio flux density has been discussed for quite some time (e.g., Ackermann et al. 2011a, and references therein). In this paper we will base all our calculations on the observational constraints listed above. Based on point (i) above we therefore assume that the γ -ray to radio flux density ratio, f_γ/f_r , is independent of redshift, and, in line with the minimal assumption approach of Paper I (and consistently with observational data), we assume that this ratio is also independent of luminosity; hence $f_\gamma/f_r = F(CD, \nu_{\text{peak}}^S)$.

Since the CD distribution depends on ν_{peak}^S , for $\nu_{\text{peak}}^S < 10^{14}$ Hz we use a linear dependence on CD with parameters derived from the sample of radio selected blazars: $\log f_\gamma/f_{5\text{GHz}} = 0.5 \times \log(CD) - 8.0$ (where f_γ is in units $\text{ph cm}^{-2} \text{ s}^{-1}$ and $f_{5\text{GHz}}$ is in Jansky). For higher ν_{peak}^S values, where inverse Compton scattering occurs in the Klein-Nishina regime and all sources have $CD \approx 1$, we use instead a correlation between the γ -ray to radio flux ratio and ν_{peak}^S , that is $\log f_\gamma/f_{5\text{GHz}} = 0.13 \times \log(\nu_{\text{peak}}^S) - 9.8$.

2.2 Simulation steps

Our Monte Carlo simulations consist of the sequential execution of the following steps:

(i) all those described in detail in Paper I to simulate the radio through X-ray SED of blazars. In short, these include (readers familiar with Paper I can skip directly to point (ii)): a) drawing values of the radio luminosity and redshift based on our assumed luminosity function (LF) and evolution (see below); b) drawing a value of the Lorentz factor of the electrons radiating at the peak of the synchrotron power and, based on that, calculate ν_{peak}^S , assuming a simple synchrotron self-Compton model (with $B = 0.15$ Gauss and a Doppler factor δ randomly drawn from a gaussian distribution with $\langle \delta \rangle = 15$ and $\sigma = 2$); c) calculating the observed radio flux density and the non-thermal emission in the optical and X-ray bands; d) adding an accretion component (only for beamed FR II sources), re-scaling an SDSS quasar template to a value, which depends on radio power; e) drawing a value of the EW of Ly α , C IV, C III, Mg II, H β , H α starting from the EW distribution of the broad lines of SDSS radio quiet QSOs; f) adding the optical light of the host galaxy assuming a standard giant elliptical as observed in blazars; g) calculating the total optical light and the observed EW of all the broad lines by taking into account the dilution due to the non-thermal and host galaxy optical light. In order to keep our simulations as simple as possible, we used no joint probability distributions during the process. In fact, as already discussed in Paper I, some of the observed correlation between different blazar quantities could be well reproduced as selection effects in a simple scenario with no intrinsic correlations;

(ii) as regards the LF, since the radio powers of γ -ray-selected sources reach lower values than the radio-selected ones, we extrapolated the radio LF of Paper I, that is $\Phi(P) \propto P^{-3}$ (in units of $\text{Gpc}^{-3} \text{ P}^{-1}$) by a factor ~ 4 down to $5.0 \times 10^{23} \text{ W/Hz}$ assuming the same slope. As for the evolution, we use the same model of the type $P(z) = (1+z)^{k+\beta z}$, which allows for a maximum in the luminosity evolution followed by a decline, with $k = 7.0$ and $\beta = -1.5$ (which implies a peak at $z \sim 1.78$). This is only slightly different (within 1σ) from the k value used in Paper I ($k = 7.3$, while β is the same) but it gives a better agreement with the γ -ray observables without affecting the results of Paper I, as discussed in Sect. 5.4 of that paper.

As detailed in Paper I, we take into account the well-known observational result that low-power radio sources display a much weaker cosmological evolution than high-power ones by having a fraction of non-evolving sources

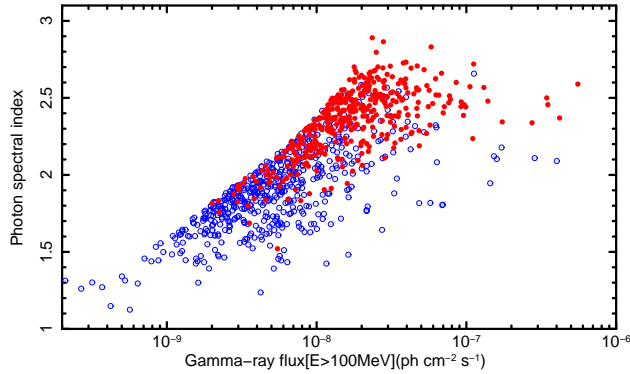


Figure 2. The spectral index of blazars in our simulated survey of 1,000 γ -ray sources is plotted against γ -ray flux. FSRQs are plotted as filled red circles, BL Lacs as open blue circles. The flux cut applied reproduces the sensitivity limits of *Fermi*-LAT in the 2LAC catalogue (see Fig. 14 of Ackermann et al. 2011b).

equal to 1 for $P_r \leq 5 \times 10^{24} \text{ W Hz}^{-1}$ and decreasing monotonically with power to 0 for $P_r \geq 5 \times 10^{27} \text{ W Hz}^{-1}$;

(iii) for sources with $\nu_{\text{peak}}^S < 10^{14} \text{ Hz}$ draw a value of the CD from the distribution shown as a green line in Fig. 1 and then use the f_γ/f_r – CD correlation, while for those with $\nu_{\text{peak}}^S > 10^{14} \text{ Hz}$ use the f_γ/f_r – ν_{peak}^S correlation (Sect. 2.1). Get f_γ by multiplying the resulting $f_\gamma/f_{5\text{GHz}}$ by the radio flux density calculated above;

(iv) obtain a value of the γ -ray spectral index from the correlation with ν_{peak}^S described in Sect. 2;

(v) apply the *Fermi* 2LAC sensitivity limits, which are a strong function of the γ -ray spectral index as shown in Fig. 14 of Ackermann et al. (2011b). The same plot for our simulation is shown in Fig. 2.

As done in Paper I, we classify a source as an FSRQ if the rest-frame EW of at least one of the broad lines that enter the optical band in the observer frame (which we assume to cover the 3,800 – 8,000 Å range) is $> 5 \text{ Å}$. Otherwise, the object is classified as a BL Lac, unless the host galaxy dominates the optical light causing the Ca H&K break to be larger than 0.4, in which case the source is classified as a radio galaxy. A BL Lac whose maximum EW is $< 2 \text{ Å}$, or for which the non-thermal light is at least a factor 10 larger than that of the host galaxy, is deemed to have a redshift which cannot be typically measured.

3 RESULTS: COMPARING SIMULATIONS WITH *Fermi* γ -ray DATA

We now make a detailed comparison between the results of our simulations and the observational data from the 2LAC “clean sample” (Ackermann et al. 2011b) in terms of fractions of BL Lacs and FSRQs, and redshift, ν_{peak}^S , and γ -ray spectral index means and distributions. To include the latest measurements we have updated the optical classifications and redshift estimates of the “clean sample” using the recently published spectroscopy results of Shaw et al. (2013). As stressed in Paper I, the aim of our simulations is *not* to reproduce the fine observational

Table 2. Results from a simulation of a γ -ray survey

Source type	Number of sources*	$\langle z \rangle^*$	$\langle \log \nu_{\text{peak}}^S \rangle^*$	$\langle \Gamma \rangle^*$
FSRQs	349.4	1.23	13.15	2.34
BL Lacs	549.6 (277.3)**	0.58	14.99	1.89
Radio galaxies	101.0	0.06	12.98	2.39
Total	1,000.0	0.82	14.15	2.10

*Average of 10 runs each simulating 1,000 sources

**BL Lacs with measurable redshift

Table 3. 2LAC data

Source type	Number of sources	$\langle z \rangle$	$\langle \log \nu_{\text{peak}}^S \rangle$	$\langle \Gamma \rangle$
FSRQs	309	1.18	13.23 (72%*)	2.36
BL Lacs	418 (168)**	0.44	15.05 (76%*)	1.98
Unclass. blazars	128 (14)**	0.32	15.14 (52%*)	2.07

*Percentage of sources with measured ν_{peak}^S

**Sources with measured redshift

details. Our approach is instead to reach robust conclusions keeping the number of assumptions to a minimum. Our simulations include 1,000 γ -ray detected blazars, a number similar to that observed in the 2LAC catalog. To ensure statistical stability of the results the simulation was repeated ten times and the results were averaged.

Table 2 summarizes our main results by giving the number of sources per class and their mean redshift, ν_{peak}^S , and γ -ray spectral index. The number in parenthesis refers to the BL Lacs with measurable redshift, to which the mean redshift pertain. Table 3 gives instead the observed values for the 2LAC sample, where the numbers in parenthesis in the ν_{peak}^S column give the fraction of sources for which this parameter could be estimated.

About 61% of our blazars are classified as BL Lacs. This agrees well with the observed value, which ranges between $56 \pm 4\%$ and $64 \pm 4\%$ (where the 1σ errors are based on binomial statistics: Gehrels 1986). The first number is derived by assuming that the unclassified blazars in Ackermann et al. (2011b) are all FSRQs while the second one presumes that they are all BL Lacs. Given that their mean ν_{peak}^S and γ -ray spectral index are closer to those of BL Lacs, the second value appears more realistic.

The 2LAC mean value is also in good agreement with the mean redshift for our simulated FSRQs (1.18 vs. 1.23), while for BL Lacs it is somewhat smaller (0.44 vs. 0.58). Fig. 3 shows the overall agreement between our simulated redshift distributions (where we have only included sources with a measurable redshift) and the observed ones.

70% of the BL Lacs (44% of those with redshift) have a standard accretion disk and are therefore FSRQs, which are classified as BL Lacs only because their observable emission lines are swamped by the non-thermal continuum, as was the case for many radio-selected blazars in Paper I.

About 50% of our BL Lacs have a redshift determination, which is close to the 2LAC value of $40 \pm 4\%$ (Shaw et al. 2013). As stated in Ackermann et al.

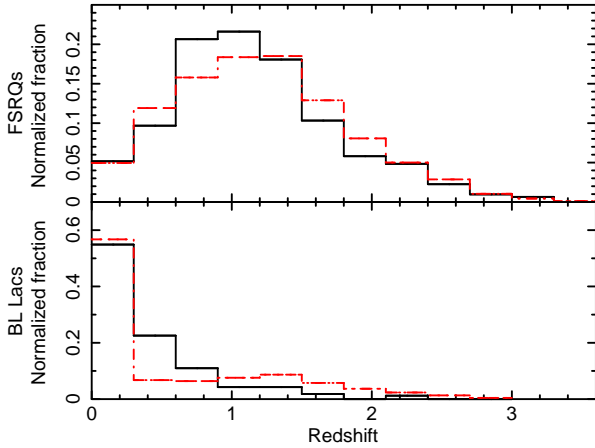


Figure 3. The redshift distribution of the blazars in the 2LAC catalogue (Ackermann et al. 2011b; Shaw et al. 2013) (black solid histogram) and that of our simulations (red dot-dashed histogram) for FSRQs (top panel) and BL Lacs (bottom panel).

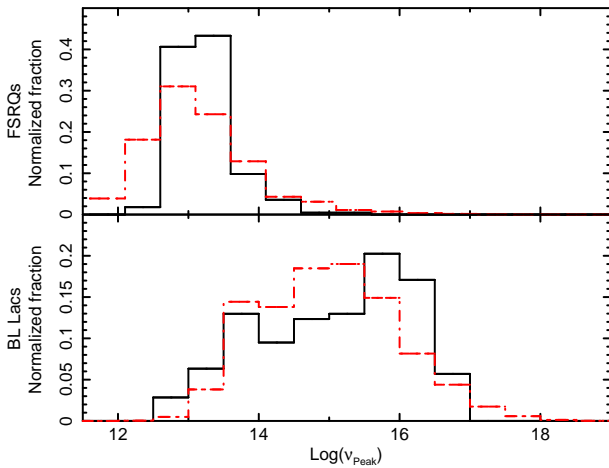


Figure 4. The distribution of synchrotron peak energies for blazars in the 2LAC catalogue (black solid histogram) and that of our simulations (red dot-dashed histogram) for FSRQs (top panel) and BL Lacs (bottom panel).

(2011b), many of the unclassified blazars do not have an optical spectrum so we cannot include them in the evaluation of the fraction of BL Lacs for which a redshift could not be obtained because they were totally featureless. According to our simulations, the “real” redshift of featureless BL Lacs ranges typically between 0.5 and 2.5, which is much larger than that of those with redshift. Basically all of these sources possess an accretion disk and therefore are FSRQs.

A small fraction ($\sim 10\%$) of the simulated blazars are classified as radio galaxies, again as was the case in Paper I. These are bona-fide blazars misclassified because their non-thermal radiation is not strong enough to dilute the host galaxy component. Their relevance is discussed in Sect. 4.5.

The predictions for ν_{peak}^S agree well with observations, as shown in Tab. 2 and 3. The 2LAC mean value is $\langle \log \nu_{\text{peak}}^S \rangle = 15.07$ if one includes the unclassified blazars with the BL Lacs. Fig. 4 compares the distributions of

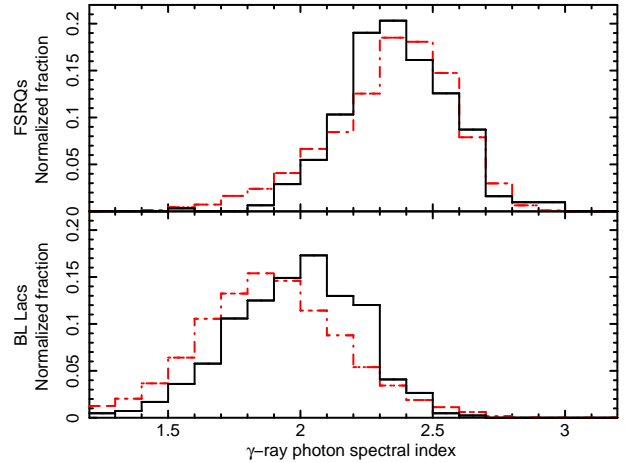


Figure 5. The γ -ray spectral (photon) index distribution of FSRQs (top panel) and BL Lacs (bottom panel). Black solid and red dot-dashed histograms represent 2LAC and simulated blazars respectively.

ν_{peak}^S for sources classified as FSRQs and BL Lacs in our simulation with those of the 2LAC blazars. The agreement is clearly quite good and reproduces the well known fact that γ -ray-selected BL Lacs tend to have ν_{peak}^S values significantly higher than FSRQs (Abdo et al. 2010b; Giommi et al. 2012b). One caveat here is that only about 3/4 of 2LAC blazars have ν_{peak}^S values, which moreover were not estimated from a fit to the SED but by using the radio-optical and X-ray-optical broadband indices.

The ν_{peak}^S values for our simulated BL Lacs without redshift peak at $\sim 10^{15}$ Hz, as for the 2LAC sources. Only $\sim 10\%$ of simulated BL Lacs are Low Synchrotron Peaked (LSP: $\nu_{\text{peak}}^S < 10^{14}$ Hz), with $\sim 33\%$ being Intermediate Synchrotron Peaked (ISP: 10^{14} Hz $< \nu_{\text{peak}}^S < 10^{15}$ Hz) and $\sim 57\%$ High Synchrotron Peaked (HSP: $\nu_{\text{peak}}^S > 10^{15}$ Hz). The corresponding 2LAC values are $\sim 20\%$, $\sim 25\%$, and $\sim 55\%$, which are not too different, considering also the caveat mentioned above. Very similar fractions ($\sim 23\%$, $\sim 20\%$, and $\sim 57\%$) are obtained by including with the BL Lacs the unclassified blazars.

Finally, the γ -ray spectral photon indexes are also consistent with observations, with a 2LAC mean value of $\langle \Gamma \rangle = 2.00$ if one includes the unclassified blazars with the BL Lacs. Fig. 5 compares the distributions for our simulated FSRQs and BL Lacs with those of the 2LAC blazars. Despite the slight shift in the peak of the distribution for BL Lacs, the agreement is again quite good and reproduces the well known fact that γ -ray-selected BL Lacs tend to have γ -ray spectral indexes flatter than those of FSRQs (e.g. Ackermann et al. 2011b, and references therein).

3.1 γ -ray predictions for radio selected blazars

To further check our scenario and verify that we are consistent with the observational constraints listed in Sect. 2, we have simulated a sample of radio selected blazars with a flux density limit of 1 Jy. We have then compared our γ -ray predictions with the *Fermi*-LAT results for the sample of radio bright blazars reported in Giommi et al.

(2012b). We find that about 71% and 91% of simulated radio selected FSRQs and BL Lacs respectively are above the *Fermi* 2LAC sensitivity limit. These percentages compare very well with the observed *Fermi*-LAT detection rate for FSRQs ($71^{+16}_{-13}\%$) and BL Lacs ($100^{+0}_{-33}\%$) in the radio sample.

Ackermann et al. (2011b) showed that the redshift distribution of γ -ray selected blazars is very similar to that of bright radio selected blazars (see their Fig. 13 for a comparison of the 2LAC and the WMAP blazar samples). The redshift distributions of our simulated radio and γ -ray selected blazars are also very similar with average values close to the observed values $\langle z \rangle_{\text{radio}} = 1.2$ and $\langle z \rangle_{\gamma\text{-ray}} = 1.2$ for FSRQs, and $\langle z \rangle_{\text{radio}} = 0.7$ and $\langle z \rangle_{\gamma\text{-ray}} = 0.6$ for BL Lacs with redshift determination. We make one more comparison between simulations and observations in Sect. 4.3.

Given the similarities in the redshift distributions and considering that the γ -ray to radio flux density ratio is independent of redshift, we expect the cosmological evolutionary properties of radio and γ -ray selected blazars to be the same.

3.2 Assessing the stability of our results

As we did in Paper I we assessed the dependence of our results on the adopted LF and evolution by making two checks: first, we varied their input values by 1σ ; second, we used as an alternative LF the sum of the BL Lac and FSRQ LFs based on the beaming model of Urry & Padovani (1995) (converted to $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$) assuming, for consistency with the way they were derived, a pure luminosity evolution of the type $P(z) = P(0)\exp[T(z)/\tau]$, where $T(z)$ is the look-back time, and $\tau = 0.33$ (consistent with the evolution of DXRBS FSRQs and BL Lacs combined, based on the samples in Padovani et al. 2007). We also tested the sensitivity of our simulations to different assumptions on the Doppler factors using distributions with mean values that ranged between 5 and 30 depending on the radio luminosity of the simulated blazar.

In all cases our main results, that is the prevalence of BL Lacs in γ -ray selected samples and the higher redshifts, lower ν_{peak}^S , and larger γ -ray spectral indexes of FSRQs were confirmed, which shows that they are independent of the details of the LF, evolution, and assumed Doppler factor.

4 DISCUSSION

4.1 *Fermi* BL Lacs without redshift

Despite extensive spectroscopic observations $56 \pm 5\%$ of the BL Lacs in the 2LAC do not have a redshift determination due to the lack of features in their optical spectrum (Ackermann et al. 2011b). This high fraction of redshift-less blazars is matched very well by our simulations, which indeed predict a value $\sim 50\%$. Most of these sources are of the HSP type, $\sim 1/3$ are ISP, while only $\sim 1/10$ are LSP. These fractions are also in agreement with what is observed in the 2LAC sample.

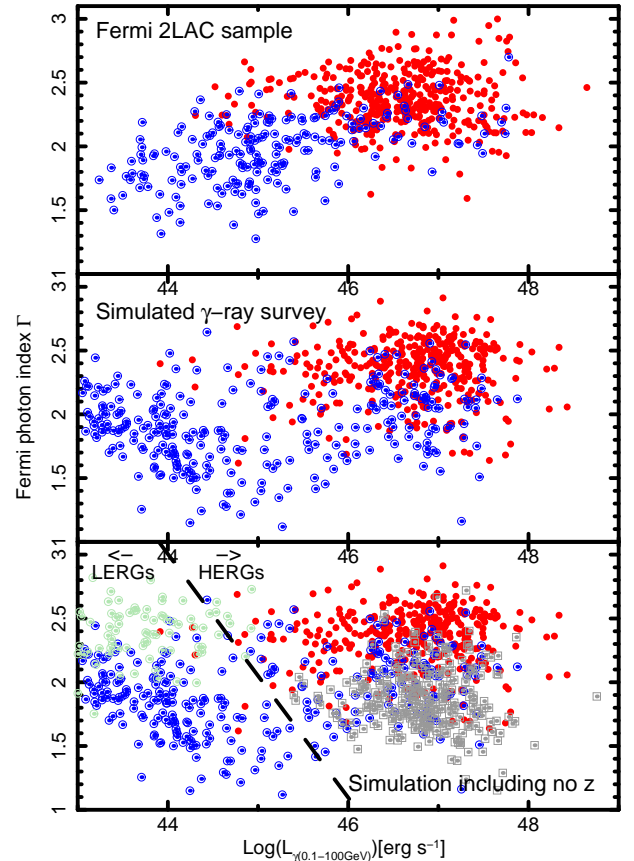


Figure 6. The γ -ray spectral index vs. γ -ray luminosity plot for γ -ray flux limited samples; FSRQs: filled red circles, BL Lacs: open blue circles. Top panel: the case of the 2LAC catalogue (Ackermann et al. 2011b); middle panel: simulated γ -ray flux limited survey where objects with no redshift information are not plotted; bottom panel: simulated γ -ray survey where the blazars with no redshift determination appear as gray open squares and sources classified as radio galaxies appear as light green symbols. The dashed line gives the approximate boundary between LERG and HERG blazars in the simulation.

Our simulations imply that these sources have much larger redshifts than those of BL Lacs with redshift information: while in the latter case $\sim 62\%$ of objects have redshift $\lesssim 0.5$, in the former case redshift values range mostly between 0.5 and 2.5, with peak probability between 0.9 and 1.2. Therefore, one cannot assume for them a value typical of BL Lacs (as done by Ackermann et al. 2011b) but larger values ($z \approx 1$) need to be used. Moreover, most of these sources are predicted to be quasars with their emission lines heavily diluted by the non-thermal continuum. These should therefore be included with the FSRQs when studying number counts, cosmological evolution, and LFs, since their exclusion will bias the results.

We note that the existence of such sources has been recently confirmed at relatively high redshift. Padovani, Giommi, & Rau (2012) have studied the SEDs of eleven 2LAC blazars without spectroscopic redshift but for which a photometric redshift > 1.2 was derived by fitting SED templates to their UV-to-near-IR multi-

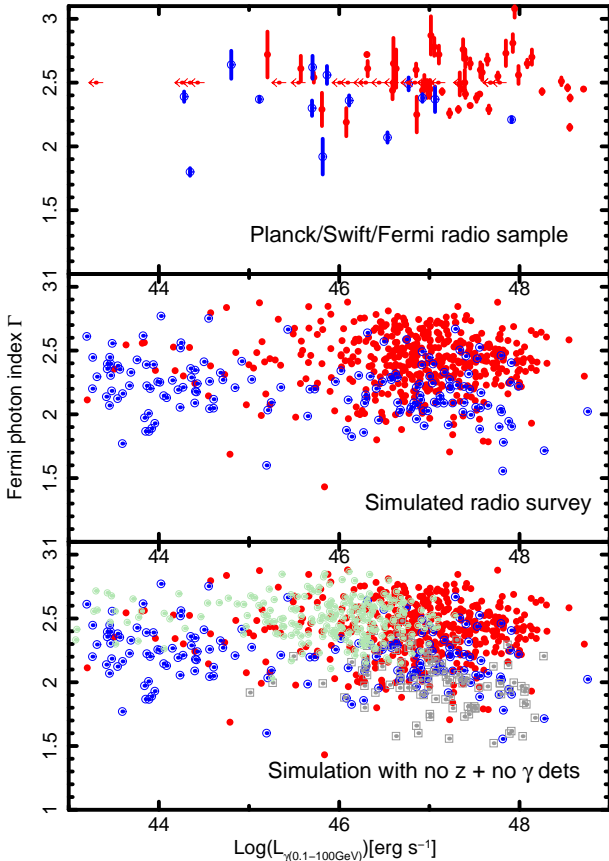


Figure 7. The γ -ray spectral index vs. γ -ray luminosity plot for radio flux limited samples; FSRQs: filled red circles, BL Lacs: open blue circles. Top panel: the case of the Planck Swift Fermi radio bright sample (data taken from Planck Collaboration 2011b); middle panel: simulated radio flux limited survey where objects with γ -ray flux below the 2LAC catalogue limit and those with no redshift information are not plotted; bottom panel: simulated radio survey where the blazars with γ -ray flux below the 2LAC limits appear as light green points and sources with no redshift determination appear as gray open squares.

band photometry obtained quasi-simultaneously with *Swift*/UVOT and GROND by Rau et al. (2012). Four blazars turned out to be of a type never seen before but with properties expected by us for some of the BL Lacs without spectroscopic redshift: large ν_{peak}^S ($\sim 5 \times 10^{15}$ Hz) and high-power ($L_{\text{peak}} \approx 6 \times 10^{46}$ erg s $^{-1}$). Four more were ISP and two were LSP, all six with $L_{\text{peak}} \gtrsim 2 \times 10^{46}$ erg s $^{-1}$, which is well into the FSRQ regime. It then looks like these sources are very plausible FSRQs in disguise.

4.2 “Masquerading” BL Lacs

How can one, in practice and in general, spot the “masquerading” BL Lacs? There are a few options:

(i) if a photometric redshift estimate is available, as in the case of the sources studied by Rau et al. (2012), one can derive the radio, or synchrotron peak, power and see if they are FSRQ-like;

(ii) if infrared spectroscopy is available then there is a good chance that the source could turn out to be an

FSRQ. Our simulations of the 2LAC, in fact, imply that $\approx 50\%$ of the BL Lacs without redshift should show a strong ($\text{EW} > 5 \text{ \AA}$) H α line, which for $z \sim 1$ would fall, for example, at $\sim 1.3 \mu\text{m}$. For a further $\approx 25\%$ one should find $2 < \text{EW} < 5 \text{ \AA}$ and therefore it should be possible to assign a redshift to these sources as well;

(iii) finally, as mentioned in Sect. 3, basically all sources without redshift in the 2LAC catalogue are predicted by our simulations to have an accretion disk and therefore to be intrinsically quasars. So for this sample the mere fact of having a featureless spectrum should be enough for a source to be considered, perhaps ironically, an FSRQ with high probability. We stress that this result is sample- and flux density limit-dependent.

In summary, we notice that in our scenario the historical 5 \AA separation between BL Lacs and FSRQs has no physical meaning and that the detection of *any* line associated with the broad line region of *any* strength should be sufficient to grant a source FSRQ status.

4.3 The γ -ray - spectral slope luminosity plane

Ghisellini et al. (2011, 2012) noted a strong correlation between the 100MeV – 10GeV luminosity and the γ -ray spectral slope in the 2LAC sample, arguing that this relationship reflects a physical distinction between FSRQs and BL Lacs. In this interpretation the presence (or absence) of strong emission lines is associated to a regime of high (low) radiating efficiency and, consequently, larger (or smaller) γ -ray luminosity.

We tested if such a correlation could be induced by the *Fermi*-LAT sensitivity dependence on spectral slope by comparing the 2LAC data with our simulated γ -ray survey blazars. Fig. 6 plots the γ -ray slope vs. 100MeV – 10GeV luminosity for blazars with a measurable redshift in the 2LAC clean sample (top panel), and in our simulated survey (central panel). The trend of high-luminosity/steep γ -ray spectrum associated to FSRQs (filled red points) and low luminosity/flat γ -ray spectrum associated to BL Lacs (open blue points) is clearly present also in the simulation, with BL Lacs mostly concentrated in the flat-spectrum/low luminosity corner and FSRQs populating almost exclusively the steep spectrum/high luminosity part of the plot. If we consider also BL Lacs with no redshift determination and objects (mis)classified as “radio galaxies” (gray squares and light green open circles respectively in the bottom panel of Fig. 6) we see that the γ -ray - spectral slope luminosity plane is filled in all its quadrants, although the different densities imply that a strong correlation is still present. We note that below $\sim 10^{44}$ erg s $^{-1}$ we predict the existence of BL Lacs with photon indexes somewhat steeper than those observed in the 2LAC sample. This is likely due to our simple power law extrapolation of the radio LF and to the misclassification of some sources close to the BL Lac/“radio galaxy” border. The LF extrapolation is also behind the somewhat higher fraction of simulated sources with $\lesssim 10^{45}$ erg s $^{-1}$ as compared to the observed one.

We then conclude that the trend reported by Ghisellini et al. (2011, 2012) comes out naturally from

our simulations and reflects the complex *Fermi*-LAT sensitivity limits. However, we also note that the separation between “real” (that is, LERG) BL Lacs and FSRQs, that in our simulation fall to the left and to the right of the dashed line of Fig. 6, is in agreement with the deductions of Ghisellini et al. (2012) for sources with known redshift. In our scenario BL Lacs with no redshift are almost all expected to be to the right of the dashed line, and therefore to be HERGs and diluted FSRQs.

To better understand the γ -ray spectral slope - luminosity plane we simulated the γ -ray properties of a sample of blazars with a *radio flux density* limit equal to those of the sample considered by Planck Collaboration (2011b) and compared our expectations with the *Fermi*-LAT measurement reported by Giommi et al. (2012b).

Fig. 7 is the same as Fig. 6 for the case of a radio flux density limited sample (see Sect. 3.1). The top panel plots the γ -ray spectral slope versus luminosity for the sample described in Planck Collaboration (2011b) and Giommi et al. (2012b). The left pointing arrows represent blazars not detected even in the 27 month *Fermi*-LAT data to which a spectral slope of 2.5 was assigned. BL Lacs with no redshift determination are not plotted. The results of our simulations are shown in the middle and lower panels where we plot respectively FSRQs and BL Lacs expected to be detected by *Fermi*-LAT in a 27 month integration as red and blue points, while BL Lacs with no redshift determination are shown as gray open symbols, and blazars undetected by *Fermi*-LAT appear as light green circles.

As apparent from Fig. 7 in this radio selected sample of blazars the correlation between γ -ray spectral slope and luminosity noted by Ghisellini et al. (2011, 2012) is not present, in good agreement with our simulations. This confirms that it is crucial to fully understand the biases of the various surveys before one can draw any conclusion on the underlying physics.

4.4 The blazar γ -ray - radio flux density correlation

Correlations between the blazar γ -ray and radio flux densities have been discussed by several authors in the past few years without reaching definite conclusions. This was due to limitations connected to the availability of large and unbiased samples, lack of simultaneity, and presence of a significant number of non-detections. Recently, a consensus seems to have been reached on the existence of a correlation between the two bands, albeit with a large scatter (e.g., Ackermann et al. 2011a; Giommi et al. 2012b; León-Tavares et al. 2012, and references therein).

Fig. 8 shows the γ -ray flux vs radio flux density for our simulated γ -ray survey. This is remarkably similar to the equivalent plot based on *Fermi*-LAT data (Fig. 3 of Ackermann et al. 2011a).

Despite the large spread in f_γ/f_r , induced by the wide dynamical range of the observed CD distribution (which can result in γ -ray fluxes up to a factor 100 or more different for the same radio flux density), a correlation is clearly present in the 2LAC simulation shown in

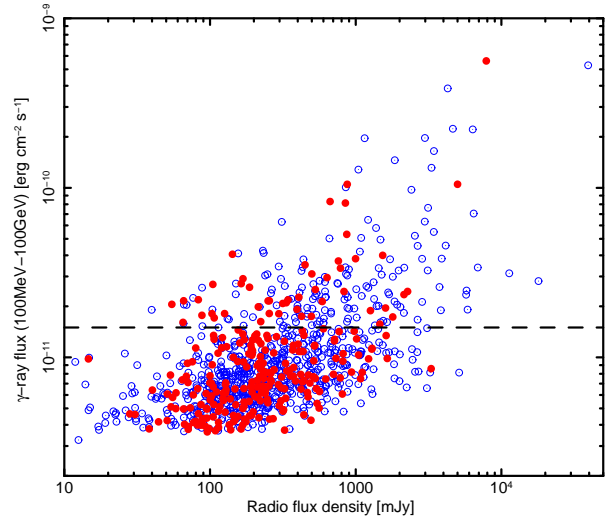


Figure 8. The γ -ray flux vs. radio flux density in our 2LAC simulated survey (reduced to 1,000 sources for better visibility). Filled red circles represent FSRQs, open blue circles represent BL Lacs. The dashed line corresponds to the γ -ray flux limit of a survey a factor ≈ 5 shallower than 2LAC.

Fig. 8. For γ -ray surveys with much shorter integration times (e.g. corresponding to the dashed line in Fig. 8), the γ -ray dynamical range decreases significantly while the radio one remains similar. This, combined with the much reduced statistics, makes it much more difficult to detect the intrinsic γ -ray-radio correlation.

4.5 *Fermi*-LAT unassociated high-Galactic latitude sources

As mentioned in Sect. 3, the scenario we propose predicts the existence of “masquerading” radio galaxies, that is blazars having their optical non-thermal emission swamped by the host galaxy. These are intrinsically rare sources with high CD values that, when detected close to the *Fermi*-LAT sensitivity limit, have a radio and optical non-thermal component significantly lower than that of blazars with smaller CD. They would then display a pure elliptical galaxy optical spectrum and would appear as radio sources typically fainter than currently known *Fermi* steep spectrum blazars (that are also characterized by large LAT error regions) thereby failing the association criteria applied by Ackermann et al. (2011b). Objects of this type could then be the counterparts of a significant fraction of the still unassociated high-latitude *Fermi* γ -ray sources, which make up $\sim 20\%$ of the total at $|b| > 10^\circ$. This is the same mechanism at work in shallow X-ray surveys where intrinsically rare objects with high f_x/f_r , that is HSP, are preferentially selected over the more common LSP.

A systematic search for such elusive counterparts of *Fermi*-LAT sources is beyond the scope of this paper and will be carried out in the future. Fig. 9 shows, as an illustrative example, the SED of SDSSJ173130.8+5429, which might be a source of this type within the error ellipse of the presently unassociated γ -ray source 2FGL J1730.8+5427.

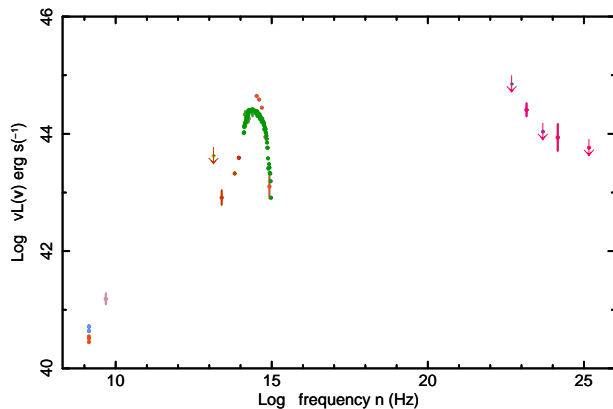


Figure 9. The SED of the radio source coincident with the 17 magnitude $z=0.238$ elliptical galaxy SDSSJ173130.8+5429 within the error ellipse of the unassociated *Fermi* γ -ray source 2FGL J1730.8+5427. An example of a high CD radio galaxy as a possible counterpart of unassociated *Fermi*-LAT high galactic latitude sources. The green line represents the template of a giant elliptical galaxy (Mannucci et al. 2001).

5 CONCLUSIONS

We have carried out Monte Carlo simulations of the radio through γ -ray emission of blazars selected in the γ -ray and radio bands within the framework of the newly proposed *simplified blazar view* presented in Paper I. We have extended these simulations to the γ -ray domain using a γ -ray to radio flux density ratio that is constrained by the relationships between SED parameters discovered by Abdo et al. (2010b) and by the distribution of Compton Dominance derived by Giommi et al. (2012b). No dependence on redshift or luminosity was assumed.

Our main results can be summarized as follows:

- (1) Our results match very well the blazar content and the observational properties of the γ -ray sources included in the 2LAC catalogue (Ackermann et al. 2011b). In particular, we reproduce all the main features of the 2LAC sample, namely the prevalence of BL Lacs, the larger redshifts and γ -ray spectral indices and lower ν_{peak}^S of FSRQs as compared to BL Lacs, and the fraction of BL Lacs without redshift, including their split in terms of ν_{peak}^S .
- (2) The simulations also reproduce well the γ -ray properties of the radio flux density limited sample considered by Planck Collaboration (2011b) and Giommi et al. (2012b).
- (3) Our simulations imply that the redshift of the BL Lacs with featureless optical spectrum is much larger than that of those with measured redshift, with values ranging from 0.5 to 2 and peak probability around 1. These sources are also predicted to possess an accretion disk and therefore not to be real BL Lacs but quasars, and as such should be considered.
- (4) The tendency for BL Lacs of appearing as low γ -ray luminosity/flat spectrum sources and of FSRQs of being high luminosity/steep γ -ray sources noted by Ghisellini et al. (2011, 2012) is also present in our simulated 2LAC survey, but not in real and simulated radio flux-density limited samples. In both our scenario and in the interpretation of Ghisellini et al. (2011, 2012) low lu-

minosity BL Lacs are low accretion LERG objects, while FSRQs and high luminosity steep spectrum BL Lacs are HERG sources; however in our simulations, contrary to the assumptions of Ghisellini et al. (2011, 2012), almost all the redshift-less BL Lacs are diluted FSRQs.

(5) The strength and large scatter of the observed γ -ray – radio flux density correlation, which has caused some discussion in the literature, are reproduced by our simulations. The latter is induced by the wide dynamical range of the observed Compton Dominance distribution.

(6) About 10% of the γ -ray sources are classified as radio-galaxies on the basis of their optical properties but are instead moderately beamed blazars with their non-thermal emission swamped by the host galaxy. These objects fail to pass the association criteria typically applied to γ -ray samples and could therefore explain a significant fraction of the still unassociated high-latitude *Fermi* sources.

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